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(54) **Title:** NANOFIBER SURFACE BASED CAPACITORS

(57) **Abstract:** This invention provides novel capacitors comprising nanofiber enhanced surface area substrates and structures comprising such capacitors, as well as methods and uses for such capacitors.

NANOFIBER SURFACE BASED CAPACITORS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit of, and priority to, U.S. Provisional Application No. 60/554,549 filed March 18, 2004. This prior application is hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

[0002] The invention relates primarily to the field of nanotechnology. More specifically, the invention pertains to capacitors comprising nanofibers and nanofiber enhanced surface areas, as well as to the use of such capacitors in various applications and devices.

BACKGROUND OF THE INVENTION

[0003] Various configurations of nanostructures (e.g., nanofibers, nanowires, nanocrystals, etc.) have attracted widespread interest for their novel properties in electrical, chemical, optical and other similar applications. Nanostructures have a broad possibility of uses, such as semiconductors for nanoscale electronics, optoelectronic applications (e.g., in lasers, LEDs, etc.) photovoltaics, sensors, etc.

[0004] Correspondingly, capacitors are pervasive electronic elements. Often, it is quite desirous to place capacitors of particular capacitance, durability, and/or construction within extremely small spaces.

[0005] In almost all instances, however, the efficiency or use of such devices is limited, at least in part, by the area of the surface which is in contact with, or comprises, the electrode plates of the capacitor. This limitation is true in several aspects. First, space limitations (or "footprint" limitations) are of concern. For example, for defined materials, a certain capacitance can exist per unit area of a surface (i.e., within a certain footprint area). Thus, the capacitance is limited by, *inter alia*, the footprint of the surfaces which comprise the capacitor. One answer to such problem is to increase the size of the footprint involved. However, besides being inelegant, such response is often problematic due to cost restraints and size limitations imposed on the footprint itself (e.g., the capacitor might need to be placed in a limited space in a device, etc.)

[0006] In a number of conventional or current applications, the surface area of a capacitor's electrode surface is increased by providing the material making up the surface with a number of holes or pores (e.g., by etching a metal plate, etc.). By providing such matrix as a porous solid, rather than just a solid surface, one increases the amount of available surface area without increasing the amount of space that the material occupies (i.e., the footprint size). While such porous matrices do increase the surface area of the electrode surface, a number of issues arise to limit the effectiveness of such measures. A final, but not trivial, problem concerns cost. Larger devices/surfaces/structures that are needed, e.g., to allow the proper capacitance, can be quite expensive.

[0007] Thus, a welcome addition to the art would be capacitors (and devices, etc. comprising capacitors) which have enhanced surface areas which would have the benefits of, e.g., increased capacitance per unit area footprint. The current invention provides these and other benefits which will be apparent upon examination of the following.

SUMMARY OF THE INVENTION

[0008] In some aspects the current invention comprises an electric capacitor which has at least one electrode surface that comprises a plurality of nanofibers. In typical embodiments, the electrode surface is comprised of a conductive material (e.g., a metal, a semiconducting material, a polymer, a resin, etc.). In some, but not all, preferred embodiments, the electrode surface and/or the nanofibers of the electrode surface are comprised of silicon. While in some embodiments the electrode surface and its nanofibers are of the same material (e.g., silicon, etc.), in other embodiments the surface and the nanofibers are of different materials from one another. Additionally, while the nanofibers are optionally grown in place upon the electrode surface, they are also optionally grown upon a different surface and subsequently placed/attached to the electrode surface.

[0009] In other embodiments of the invention, the capacitor also comprises a dielectric of a nonconductive material which covers substantially all members of the plurality of nanofibers (and the electrode surface on which the nanofibers exist). The dielectric, thus, exists between the electrode surfaces (or "electrode plates" or the like) of the capacitor. Such dielectric can optionally be composed of one or more of a number of materials, e.g., oxides, nitrides, various nonconductive polymers, ceramics, resins, porcelains, mica containing materials, glass, vacuum, rare earth oxides, gas (e.g., air, inert

gases, etc.), or other typical dielectrics used in electronic capacitors. Those of skill in the art are quite familiar with a broad range of materials used as dielectrics and capable of use as dielectrics in the current invention. In some embodiments, the dielectric comprises a grown oxide layer and/or a naturally occurring oxide layer. The dielectric can comprise, e.g., a metal oxide such as aluminum oxide or tantalum oxide, etc. The dielectric can also comprise silicon oxide.

[0010] In various embodiments, the dielectric, e.g., oxide layer, comprises a desired thickness (depending upon, e.g., the desired capacitance and other parameters such material construction, etc.). For example, the dielectric, e.g., oxide layer, can comprise a thickness from about 1 nm or less to about 1 um, from about 2 nm or less to about 750 nm, from about 5 nm or less to about 500 nm, from about 10 nm or less to about 250 nm, or from about 50 nm or less to about 100 um. The dielectric, e.g., oxide layer, can also comprise a thickness that is substantially equivalent to the thickness of the electrode surface(s).

[0011] In typical embodiments, the capacitors herein also comprise a second electrode surface. Such second surface can comprise, e.g., a layer of material deposed upon the dielectric which covers the plurality of nanofibers and the first electrode surface. In such embodiments, the second surface material can comprise a conductive material (e.g., similar to the optional composition of the first electrode surface such as a metal, a semiconducting material, a polymer, a resin, etc.). In various embodiments, the two electrode surfaces can be of the same composition, or can be of different composition. In some embodiments, the second surface comprises an evaporated or sputtered electrically conducting material. Such evaporated/sputtered materials can include, e.g., aluminum, tantalum, platinum, nickel, a semiconducting material, polysilicon, titanium, titanium oxide, an electrolyte, gold, etc.

[0012] The various embodiments of capacitors herein can have a number of different densities of nanofibers per unit area outline (i.e., per footprint area). For example, the density of the members of the plurality of nanofibers can range from about 0.11 nanofiber per square micron or less to at least about 1000 nanofibers per square micron, from about 1 nanofiber per square micron or less to at least about 500 nanofibers per square micron, from about 10 nanofibers per square micron or less to at least about

250 nanofibers per square micron, or from about 50 nanofibers per square micron or less to at least about 100 nanofibers per square micron.

[0013] Also, in various embodiments (e.g., in those wherein the nanostructures comprise nanofibers, nanowires, or the like as opposed to nanocrystal or other similar nanostructures whose structural profile is not substantially cylindrical or tubular), the length of the members of the plurality of nanofibers can optionally range from about 1 micron or less to at least about 500 microns, from about 5 micron or less to at least about 150 microns, from about 10 micron or less to at least about 125 microns, or from about 50 micron or less to at least about 100 microns; and wherein the diameter of the members of the plurality of nanofibers ranges from about 5 nm or less to at least about 1 micron, from about 10 nm or less to at least about 500 nm, from about 20 nm or less to at least about 250 nm, from about 20 nm or less to at least about 200 nm, from about 40 nm or less to at least about 200 nm, from about 50 nm or less to at least about 150 nm, or from about 75 nm or less to at least about 100 nm.

[0014] In yet other embodiments, the capacitors of the invention can comprise an electrode surface that, because of the nanofibers present, is considerably greater in surface area than other typical electrode surfaces of similar or substantially equal footprint. For example, the density of the members of the plurality of nanofibers can optionally increase the surface area of the electrode surface from at least 1.5 times to at least 100,00 times or more, at least 5 times to at least 75, 000 times or more, at least 10 times to at least 50,000 times or more, at least 50 times to at least 25,000 times or more, at least 100 times to at least 10,000 times or more, or at least 500 times to at least 1,000 times or more, greater, in comparison to an area of substantially equal footprint of an electrode surface without nanofibers

[0015] Additionally, in other embodiments, the capacitors of the invention can comprise a farad capacity that, because of the nanofibers present, is considerably greater in amount than that of other typical electrode surfaces of similar or substantially equal footprint. For example, the farad capacity of the capacitors of the invention can comprise from about at least 1.5 times to at least 100,00 times or more, at least 5 times to at least 75, 000 times or more, at least 10 times to at least 50,000 times or more, at least 50 times to at least 25,000 times or more, at least 100 times to at least 10,000 times or more, or at least 500 times to at least 1,000 times or more greater capacitance than a capacitor having an

electrode surface of substantially equal footprint but not comprising a plurality of nanofibers.

[0016] In yet other aspects, the invention comprises a device which comprises any of the capacitors of the invention. For example, timepieces, remote controls, medical devices, radios, computers, electronic equipment, etc. which have a capacitor herein are also aspects of the invention.

[0017] These and other objects and features of the invention will become more fully apparent when the following detailed description is read in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] **FIGURE 1,** Displays a schematic diagram of a generalized capacitor.

[0019] **FIGURE 2,** Displays a schematic diagram representing an enhanced surface area capacitor.

[0020] **FIGURE 3, Panels A and B,** Display photomicrographs of enhanced surface area substrates such as can form the basis for enhanced surface area capacitors.

[0021] **FIGURE 4,** Displays a graph comparing the surface area of a nanofiber enhanced area against varying distances between nanofibers.

DETAILED DESCRIPTION

[0022] The current invention comprises a number of different embodiments focused on nanofiber enhanced area surface substrates and uses thereof in capacitors. As will be apparent upon examination of the present specification, figures, and claims, substrates having such enhanced surface areas present improved and unique capacitance aspects that are beneficial in a wide variety of applications ranging from materials science to medical use and beyond. It will be appreciated that enhanced surface areas herein are sometimes labeled as "nanofiber enhanced surface areas" or, alternatively depending upon context, as "nanowire enhanced surface areas," etc.

[0023] A common factor in the embodiments is the special morphology of nanofiber surfaces (typically silicon oxide nanowires herein, but also encompassing other compositions and forms). For example, the vastly increased surface area presented by

such substrates is utilized in, e.g., creation of improved capacitors for a wide variety of uses. In most aspects herein, it is thought that such benefits accrue from the unique morphology of the nanofiber surfaces (especially form the vastly increased surface area), but the various embodiments herein are not necessarily limited by such theory in their construction, use, or application. In some embodiments, the nanofibers are optionally functionalized with one or more entity.

[0024] Again, without being bound to a particular theory or mechanism of operation, the concept of the majority of benefits of the invention is believed to operate, at least in part, on the principle that the nanofiber surfaces herein present a greatly enhanced surface area in relation to the same footprint area without nanofibers.

Capacitors

[0025] Capacitors, in general and in specific applications, are quite well known in the art. Various types of capacitors, e.g., electrolytic capacitors, are replete throughout the literature. Figure 1 shows the basic components of a capacitor in a generalized fashion. In typical capacitors, a dielectric material is layered between two conductive electrodes (typically metal). An electrical charge proportional to the voltage can then be stored in the capacitor when a voltage is applied across the electrodes. Thus, in Figure 1, electrodes 100 and 200 (alternately termed "electrode plates," "electrode surfaces," or "opposing plates" or the like) are separated by dielectric, 300. The electrodes are typically electrically connected to other components via connections such as 400. The capacitance "C" of a parallel-plate capacitor is given by Equation 1.

Equation 1:

$$C = \frac{\varepsilon_0 K_d A}{d}.$$

In Equation 1, "A" represents the area of the two plates in the capacitor, while "E_0" represents the dielectric permittivity of vacuum or free space (8.85 x 10-12F/m). "K_d" represents the dielectric constant of the dielectric and "d" is the distance between the two plates of the capacitor. As can be seen, capacitance depends upon the thickness of the dielectric (e.g., the distance between the electrodes), the dielectric constant of the dielectric, and the area (or effective area) of contact between the plates of the capacitor. Thus, greater capacitance can be achieved through, e.g., increasing the dielectric constant